Fermi National Accelerator Laboratory

FERMILAB-Pub-88/158-A
October 1988

AXIONS AND SN 1987A

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ABSTRACT

Consideration of axion emission from the newly-born neutron star associated with SN 1987A leads to the most stringent and probably most reliable astrophysical bound to the axion mass: the duration of the neutrino pulse observed by the KII and IMB detectors precludes an axion with mass in the range 2 eV to 10^{-3} eV, a bound applicable to both DFS and hadronic type axions. For an axion of mass greater than $\sim$ 2 eV axions are so strongly trapped in the core that their emission is highly suppressed. Herein I describe the calculation of the axion emission rate for the primary process, nucleon, nucleon axion bremsstrahlung, the incorporation of axion cooling into a variety of realistic numerical models of the initial cooling phase of the neutron star, and the response of the KII and IMB detectors to the predicted neutrino flux. The details of the work summarised here are published in collaborative works with Burrows and Brinkmann.[1]

1. Introduction

The axion is the hypothetical pseudo Nambu-Goldstone boson associated with the spontaneous breakdown of the Peccei-Quinn quasi symmetry. In 1977 Peccei-Quinn (PQ) symmetry was proposed as a solution to the 'strong CP problem'; today, a decade later, PQ symmetry still stands as the most attractive solution to this nagging problem[2], a singular blemish on the beautiful theory of QCD. The original axion with symmetry breaking scale equal to the electroweak scale was quickly ruled out both by laboratory experiments and on astrophysical grounds (axion emission from red giant stars[3]). To wit, the 'invisible axion' was introduced,[4,5] with essentially arbitrary symmetry breaking scale $f_a \gg 300$ GeV. Generically, invisible axions are of two types: Dine-Fischler-Srednicki[4] (DFS) and hadronic.[5] The DFS axion couples fundamentally to all fermions with strength $\sim m_f/f_a$, while the hadronic axion only couples fundamentally to quarks, and possibly only to very heavy, exotic quarks. Both types of axions couple to photons and gluons (through anomalies) and to nucleons (through axion-pion mixing). The axion mass is related to the PQ symmetry breaking scale f_a by:

$$m_a \simeq 0.62\text{eV}\,[10^7\text{GeV}/(f_a/N)],$$

where N is the color anomaly of the PQ symmetry.[6] Note, the fact that $m_a \propto f_a^{-1}$ implies that the axion couples proportionally to its mass.

Cosmology and astrophysics set very stringent bounds to the axion mass. Cosmologically produced axions contribute excessive mass density today, unless[7]

$$m_a \gtrsim 3.6 \times 10^{-6} \gamma^{-0.85} \Lambda_{200}^{-0.6} \mathrm{eV}$$

where $200\Lambda_{200}$ MeV is the QCD scale parameter, and $\gamma \geq 1$ accounts for any entropy production in the Universe after the axions are produced: $\gamma =$ (entropy after)/(entropy before). Because axions are very light particles and interact very weakly they are produced in the interiors of stars and stream out freely. Thus, if the axion exists, axions hasten the loss of nuclear free energy by stars and thereby accelerate stellar evolution. At present the most stringent strophysical limits follow from considering the evolution of red giant stars;[8] these limits depend upon the coupling of axions to electrons and photons and thus are different for DFS and hadronic axions:

$$m_a \lesssim 0.01 \mathrm{eV} \quad \mathrm{DFS} \qquad m_a \lesssim 2 - 30 \mathrm{eV} \quad \mathrm{HADRONIC}$$

The latter limit depends upon the axion's anomalous coupling to 2 photons and is model-dependent. As we shall see, the SN 1987A limit has the advantage of being insenitive to the model or type of axion, as well as being considerably more stringent.

2. Axion Emission from SN 1987A

SN 1987A not only confirmed astrophysicists' more cherished beliefs about type II (core collapse) supernovae, but also provided a unique laboratory for the study of the properties of ordinary neutrinos, right-handed neutrinos, axions, and other exotic hypothetical particles. Shortly after the bounce of the 1.4 $M_\odot$ Fe core, the central temperature was 20-70 MeV and the central density $\sim 8 \times 10^{14}$ g cm^{-3}. Under such conditions the dominant axion emission process is nucleon-nucleon, axion bremsstrahlung.[9] In the one pion exchange approximation (OPE) there are 4 direct and 4 exchange diagrams, shown in Fig. 1. The relevant axion coupling is that to nucleons, which is relatively insensitive to the type of axion and is of order $m_N/(f_a/N) \simeq 10^{-7}(m_a/\mathrm{eV})$. We have evaluated the full matrix element squared (64 terms) exactly. From $|\mathcal{M}|^2$ the axion emission rate (per volume per time) is given as

$$\dot{\varepsilon}_a = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_a (2\pi)^4 S |\mathcal{M}|^2 \delta^4(p_1+p_2-p_3-p_4-p_a) E_a f_1 f_2 (1-f_3)(1-f_4)$$

where $d\Pi_i = d^3p_i/(2\pi)^3 2E_i$, the labels $i = 1-4$ refer to the incoming (1,2) and outgoing (3,4) nucleons, $i = a$ denotes the axion, S is the symmetry factor for identical particles in the initial and final states, $|\mathcal{M}|^2$ is summed over initial and final nucleon spins, and the nucleon phase space distribution functions are $f_i = [\exp(E_i/T - \mu_i/T) + 1]^{-1}$. The emission rate is relatively easy to evaluate in the fully degenerate or non degenerate regimes; however, the nucleons in the core are semi-degenerate, $\epsilon_{FERMI} \sim T$. In addition, since the post collapse core has roughly equal numbers of neutrons and protons, 3 bremsstrahlung processes are important: $nn \to nn + a$, $pp \to pp + a$, and $np \to np + a$. We have numerically evaluated the axion emission rate, for all 3 processes and arbitrary nucleon degeneracy (see Fig. 2).

3. The Effect of Axion Cooling on the SN 1987A Neutrino Burst

In the catastrophic collapse of the Fe core of a massive star about 3×10^{53} ergs of binding energy are liberated, and according to the standard picture, this energy is radiated in thermal neutrinos of all 3 types. The neutrino mean free path within the core is much smaller than the size of the core (~ 10 km) and so neutrinos are trapped in the core and radiated from a neutrino sphere ($R \sim 15$ km, $\rho \sim 10^{12}$g cm^{-3}, $T \sim 4$ MeV). Neutrino emission is characterized by two phases: the first is powered by residual accretion and hydrodynamic contraction of the outer core, and lasts 1-2 sec; the second phase is powered by the diffusion of heat trapped in the inner core region, and lasts $\sim 5 - 10$ sec, the timescale for neutrino diffusion from the core to the neutrino sphere. The energies associated with the two phases are comparable. The observations of KII[10] and IMB[11] are both qualitatively and quantitaively consistent with the standard picture.

Axions less massive than about 0.02 eV once radiated freely stream out of the nascent neutron star, and thereby accelerate the cooling. Qualitatively then, one would expect axion emission to shorten the duration of the neutrino pulse—this is in fact what occurs (see Fig. 3). [Of course axion emission, which proceeds most strongly from the high temperature, high density inner core does not directly affect neutrino emission, which proceeds from the neutrino sphere (in the outer core).] We have incorporated axion cooling into realistic numerical models of the collapse and initial cooling of the nascent neutron star;[12] the biggest theoretical uncertainty in these models is the equation of state (EOS) above nuclear density, densities which are achieved in the core during and after collapse. We have allowed for a wide range of EOS's, from a very stiff EOS to a very soft EOS. For our various axion-cooled, numerical models we have computed the resulting neutrino flux and the predicted response of the KII and IMB detectors: expected number of events and burst duration, $\Delta t(90\%)$, the time required for the number of events to achieve 90% of its final value. The quantity $\Delta t(90\%)$ is the most sensitive barometer of axion emission. Axion emission tends to rapidly cool the inner core, depleting the energy which powers the second part of the burst. This effect is clearly seen in Fig. 3 where $\Delta t(90\%)$ is plotted as a function of m_a. Axion emission has virtually no effect on $\Delta t(90\%)$ until a mass of $\sim 3 \times 10^{-4}$ eV, and by an axion mass of 10^{-2} eV the duration of the neutrino burst has dropped to less than a sec. For comparison, for an axion mass of 10^{-2} eV, the expected number of neutrino events has only dropped from ~ 10 to ~ 8 for KII and from ~ 6 to ~ 4 for IMB (see Fig. 4); likewise, for an axion mass of 10^{-2} eV, neutrinos still carry away more than 50% of the binding energy. The large effect on the burst duration traces to the fact that axion emission from the core efficiently radiates away the heat which powers the latter phase of the burst.

For axion masses greater than $\sim$0.02 eV axions interact sufficiently strongly so that they do not simply stream out, rather they become trapped in the core and are radiated from an axion sphere. In this case the complexity of axion transport has thus far prevented us from incorporating axion cooling into our numerical models. However, simple analytical models indicate that for an axion mass of ~ 2 eV or greater the axions are so strongly trapped that their presence is equivalent to less than a couple of additional neutrino species and is therefore consistent with the observations of KII and IMB.

4. Conclusion/Discussion

We have calculated axion emission from the nascent neutron associated with SN 1987A due to the process nucleon, nucleon axion-bremsstrahlung and incorporated this cooling mechanism into realistic numerical models of the cooling of the newly-born neutron star. We find that for an axion mass of about 10^{-3} eV axion cooling leads to a dramatic drop in the expected neutrino burst duration as axions carry away the heat in the inner core which should power the late part of the neutrino burst. For axion masses greater than about 2 eV, axions are so strongly trapped in the core that their cooling effect on the nascent neutron star should be negligible. For the DFS axion this, and other, astrophysical limits preclude $m_a \gtrsim 10^{-3}$eV, leaving a window from $\sim 10^{-6}$eV to $\sim 10^{-3}$eV—all but requiring axions to be cosmologically relevant if they exist. For the hadronic axion this, and other, limits leave two windows: the one above, and a smaller window from $\sim 2 - 30$eV—and an axion of mass $2 - 10$eV may indeed be detectable through the decays of relic axions.[15]

Two obvious uncertainties cast a shadow of doubt on our limit: the equation of state at supernuclear density and the axion emission rate. While the former is indeed an important uncertainty, we have explored a variety of EOS's and our limit does not vary significantly. The latter is of greater concern. We have calculated axion emission in the OPE approximation[16] at supernuclear densities, neglecting collective nuclear effects. While this fact rightfully gives one pause, it is reassuring that since $\dot{\varepsilon}_a \propto m_a^2$, our limit only varies as $\dot{\varepsilon}_a^{-1/2}$—a factor of 10 error in $\dot{\varepsilon}_a$ only changes our limit by a factor of 3.

Finally, we should compare our work with other similar work. Mayle, et al[13] have also used numerical cooling models to obtain a limit to the axion mass, although they have not computed the response of the KII and IMB detectors to the neutrino flux predicted by their models. They obtain a limit of $\sim 10^{-4}$ eV. However, we believe that they have overestimated axion emission by a factor of about 50, by using the degenerate regime rates; correcting for this fact their limit is comparable to ours. Raffelt and Seckel[14] have tried to incorporate axion cooling into numerical models, but without considering the back reaction of the axions on the star, and obtain a limit similar to ours (however, they too use the degenerate regime rates). In sum, we say with some confidence that we believe that the mass limit which derives from SN 1987A is 10^{-3} eV, to within a factor of 2-3.

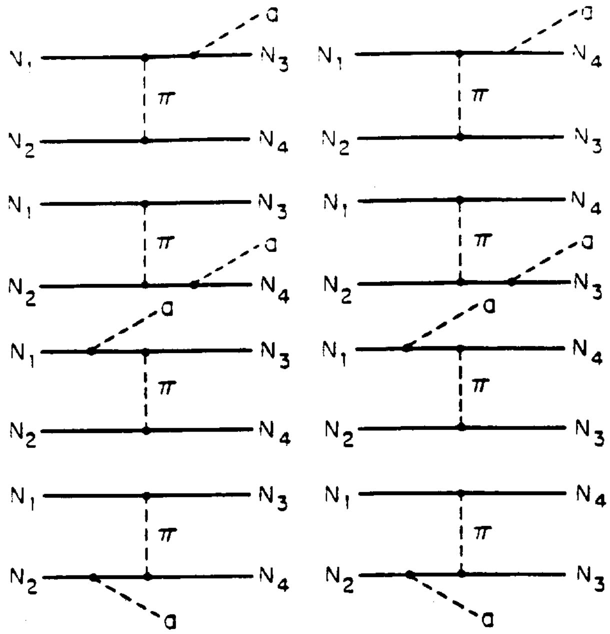

FIG. 1

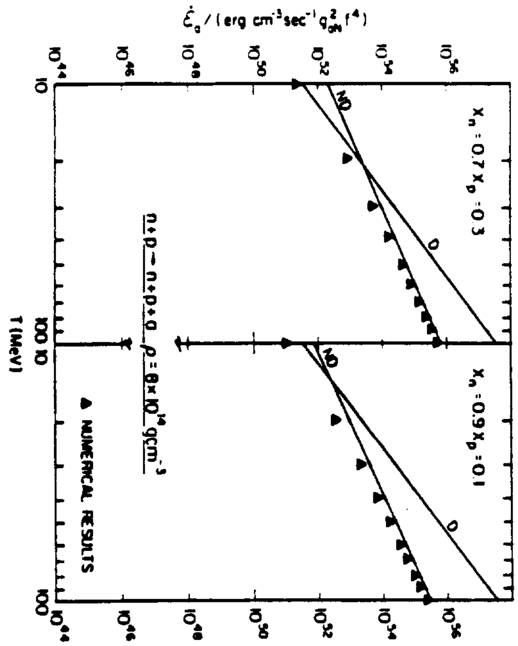

FIG. 2

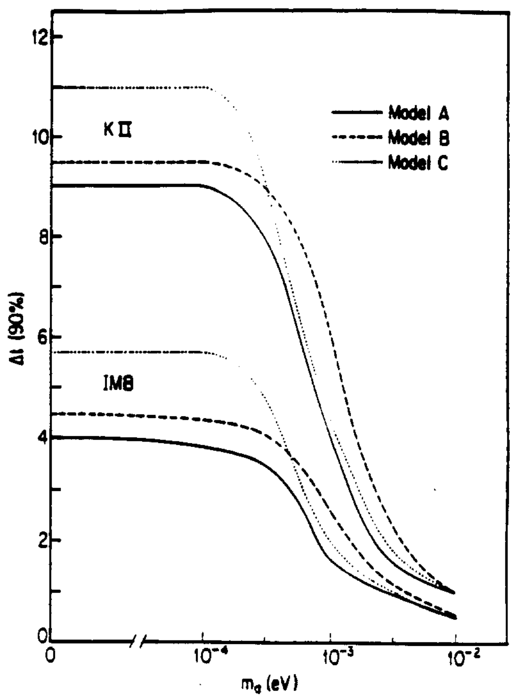

FIG. 3

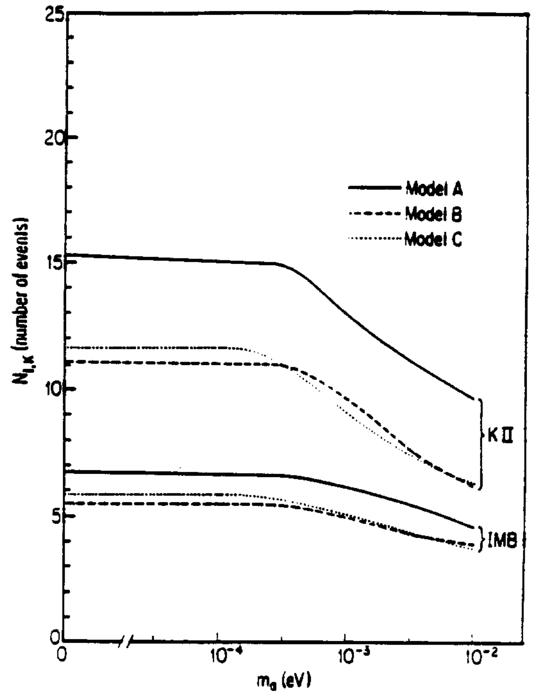

FIG. 4

Acknowledgments

This brief summary is based upon collaborative work done with Ralf Peter Brinkmann and Adam Burrows and is published in Refs. 1. This work was supported in part by the DoE (at Chicago) and by the Sloan Foundation (through a Sloan Fellowship).

References

1. M.S. Turner, *Phys.Rev.Lett.* 60, 1797 (1988); R.P. Brinkmann and M.S. Turner, *Phys.Rev.* D38 (1988); A. Burrows, M.S. Turner, and R.P. Brinkmann, *Phys.Rev.D*, in press (1988).
2. R.D. Peccei and H.R. Quinn, *Phys.Rev.Lett.* 38, 1440 (1977); F. Wilczek, *ibid* 40, 279 (1978); S. Weinberg, *ibid* 40, 223 (1978), and Refs. therein.
3. D.A. Dicus, et al, *Phys.Rev.* D18, 1329 (1978); D22, 839 (1980); K. Sato, *Prog.Theor.Phys.* 60, 1942 (1978).
4. A.R. Zhitnitsky, *Sov.J.Nucl.Phys.* 31, 260 (1980); M. Dine, W. Fischler, and M. Srednicki, *Phys.Lett.* 104B, 199 (1981).
5. M. Shifman, A. Vainshtein, and V. Zakharov, *Nucl.Phys.* B166, 493 (1980); J. Kim, *Phys.Rev. Lett.* 43, 103 (1979).
6. The normalization used here is that of M. Srednicki, *Nucl.Phys.* B260, 689 (1985); also see, D. Kaplan, *Nucl.Phys.* B260, 215 (1985), P. Sikivie, in *Cosmology and Particle Physics*, eds. E. Alvarez etal (WSPC, Singapore, 1987), and Turner in Ref. 1 for a detailed discussion of axion couplings.
7. J. Preskill, M. Wise, and F. Wilczek, *Phys.Lett.* 120B, 127 (1983); L. Abbott and P. Sikivie, *ibid*, 133 (1983); M. Dine and W. Fischler, *ibid*, 137 (1983). However, also see, R. Davis, *Phys.Lett.* 180B, 225 (1986). The limit quoted here is from M.S. Turner, *Phys.Rev.* D33, 889 (1986), where it is also noted that if the Universe inflates before or during PQ SSB, the limit quoted here depends upon the initial misalignment angle.
8. D. Dearborn, D. Schramm, and G. Steigman, *Phys.Rev.Lett.* 56, 26 (1986); G.G. Raffelt, *Phys.Lett.* 166B, 402 (1986); G.G. Raffelt and D. Dearborn, *Phys.Rev.* D36, 2211 (1987).
9. Although J. Ellis and K. Olive, *Phys.Lett.* 193B, 525 (1987) claim that $e + \gamma \rightarrow e + a$ is the dominant emission process, T. Hatsuda and M. Yoshimura, *Phys.Lett.* 203B, 469 (1988) have shown that it is subdominant by some 5 orders-of-magnitude.
10. K. Hirata etal, *Phys.Rev.Lett.* 58, 1490 (1987).
11. R.M. Bionta etal, *Phys.Rev.Lett.* 58, 1494 (1987).
12. A. Burrows and J. Lattimer, *Astrophys.J.* 307, 178 (1986); A. Burrows, *Astrophys.J.*, in press (1988).
13. R. Mayle, et al, *Phys.Lett.* 203B, 188 (1988).
14. G.G. Raffelt and D. Seckel, *Phys.Rev.Lett.* 60, 1793 (1988).
15. M.S. Turner, *Phys.Rev.Lett.* 59, 2489 (1987).
16. The validity of the OPE approximation has been addressed by K. Choi, K. Kang, and J.-E. Kim, Brown Univ. preprint HET-671 (1988), and M.S. Turner, Fermilab preprint FNAL PUB 88/ A (1988).